Rehabilitating River Valley Ecosystems: Examples of Public, Private, and First Nation Cooperation in Western Washington

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[Editor's note: Figures for Abbe et al appear at the end of this paper.]

Abstract
Prior to European colonization, lowland forest rivers of the coastal Pacific Northwest occupied vast geographic areas and were interspersed with complex networks of perennial and ephemeral channels. Floodplains mantled in complex mosaics of forest patches and wetlands were integrally linked to these channel networks. One of principal components driving the complexity of these systems was the presence of logjams, which split flow, raised water levels, created pools, and provided abundant cover for fish, particularly salmonids. Several efforts underway on the Olympic Peninsula of Washington State provide examples of integrating a valley-scale approach to rehabilitating salmonid habitat. Projects in these rivers are incorporating the construction of logjams as a key element in re-creating channel complexity in cooperative efforts with local private landowners, public agencies and First Nations. In addition, other rivers where "hands-off" management of riparian forests has led to the natural formation of large logjams, such as on the Green, Nisqually and Deschutes Rivers in the Puget Sound area which demonstrate that natural processes can still create the complex and rich ecosystems. However, the rehabilitation of forest river corridors can have significant consequences to infrastructure and development, which communities should understand and be prepared to accommodate.

Introduction
This paper briefly summarizes several collaborative efforts between First Nations, private landowners and public agencies in western Washington to better understand forest rivers and rehabilitate salmon habitat. The primary focus covers the role of logjams in large-scale habitat rehabilitation in river valleys and the potential conflicts that can arise with historic river management and development. Efforts to rehabilitate salmonid habitat have increasingly recognized the need to restore physical characteristics and processes that emulate pre-industrial conditions. The linkage between the physical characteristics of a river and fluvial processes such as flow regime, is not a one-way relationship. Physical structure such as snags and logjams can have a significant effect on channel forming processes such as re-directing flow lines, inducing scour and sedimentation, and increasing over-bank flood frequency through backwater effects (Abbe and Montgomery 1996; Gippel et al 1996; Collins et al. 2002, 2003; Abbe et al. in press). These changes can have a pronounced effect on the morphology of entire river valleys and the ecological communities within them. Little attention has been paid to the valley scale effects of wood debris in the extensive efforts to restore salmonid habitat in the Pacific Northwest (PNW) even though natural examples of these large-scale effects still occur. Recognition of the magnitude to which wood debris can affect rivers will be increasingly important as more rivers and riparian forests are restored, particularly in evaluating the extent to which property and infrastructure may be affected and ultimately adapted to sustain healthy ecosystems. The goal of this paper is to present and discuss examples from the central Cascades, Puget Sound, and Olympic Peninsula where some of the valley scale effects of logjams can still be seen, the backwater effects that can be induced by logjams, and how logjams can play an important role (Figure 1). Their application is not only in rehabilitating habitat but in mitigating the impacts of major disturbance such as dam removal.

Forested Alluvial River Valleys
Alluvial river valleys of the PNW once characterized by complex mosaics of channels and wetlands have been reduced to simple channels and floodways occupying a fraction of their original extent (e.g., Sedell and Frogatt 1984; Abbe et al. 2003; Collins et al. 2003). Forests played an important role in the morphology of alluvial rivers in the PNW. One of the most significant means by which forests influenced fluvial geomorphology was through snags and logjams that obstructed and diverted flow to create complexity through a range of scales from bed texture and channel topography to channel plan-form, the number of channels, and floodplain construction (Wolff 1916; Lisle 1995; Abbe and Montgomery 1996, Buffington and Montgomery 1999; Collins and Montgomery 2002; Abbe and Montgomery 2003, O'Connor et al. 2003). Examples of these complex environments can still be found, sometimes right next to major infrastructure (Figure 2). While logjams can beresponsible for much of the frequent disturbance and changing channel positions, they also can provide small islands of stability within a channel migration zone (CMZ) that enables some forest patches to survive for centuries (Figure 3).

Historic River Simplification
European colonization of the PNW brought about the most extensive change to river valleys in the last 10,000 years (Beechie et al. 2001; Pess et al. 2003). In addition to the immense reduction in land area once linked to fluvial processes, river ecosystems underwent a massive simplification in their physical complexity (Abbe et al. 2003; Collins et al. 2003). Less than 10% of the wetlands and floodplains once associated with lowland alluvial rivers of the Puget Sound basin remain intact (Collins and Montgomery 2003). Channel simplification resulted from aggressive efforts to improve navigation, flood control, "fish passage," agricultural and industrial development of floodplain lands, and the development of hydroelectric and water supply projects. Historic channel alterations included clearing channels of thousands of snags and logjams, construction of levees, revetments and dams. Ditching, diking, and dredging activities in floodplains, primarily found in urban and agricultural regions, were associated with 73% of the coho salmon rearing habitat losses in the Skagit River system (Beechie et al. 1994). Another widespread activity that had a significant impact on PNW rivers was the clearing of snags and logjams (Sedell and Frogatt 1984; Maser and Sedell 1994; Collins et al. 2002).

Backwater Effects of Large Logjams: Ozette and Deschutes Rivers
Removal of logjams from the Ozette River may have directly contributed to the collapse of several salmon species in the Lake Ozette watershed. The Ozette River is located at the northwest end of Lake Ozette, at the northwest tip of the Olympic Peninsula. The river's discharge is primarily a function of water elevations in Lake Ozette, the third largest lake in Washington State. The river flows approximately 9 km from Lake Ozette to the Pacific ocean and is characterized by a sinuous sand and gravel channel with a gradient of about 0.1% (Figure 4). Settlement along Lake Ozette began late in the 19th century and was later limited by inclusion of the Lake and Ozette River in Olympic National Park. While most of the Lake Ozette watershed is industrial timberland, old growth forest remains largely intact along the Ozette River and margins of the lake. The Lake Ozette system was once utilized by several salmon species, all of which experienced a dramatic decline in the early 1950s from which they have never recovered (Ward et al. 1976; Bortleson and Dion 1979). Chinook salmon (*Oncorhynchus tshawytscha*), are presumed extirpated in the Ozette River and the status of chum salmon (*O. keta*), is unknown (Makah Tribe 2000). Lake Ozette sockeye (*O. nerka*), are listed as an endangered species. Explanations for the salmon decline in the Ozette River and Lake Ozette system have been debated for last 50 years. Coincidental with the most rapid decline in salmon populations was the removal of 26 large logjams in the Ozette River and more in tributaries to Lake Ozette (Kramer 1953). Historical observations of the Lake Ozette shoreline suggest that lake levels lowered as a result of channel clearing and that gravel beaches have been transformed into finer substrates colonized by woody vegetation.

To investigate the role logjams may have had in altering habitat in the Ozette River and along the Lake Ozette shoreline, current conditions in the upper two kilometers of the river just below the lake were surveyed and the 1-D hydraulic model HEC-RAS used to predict backwater effects that may have been induced by historic logjams (PWA 2001). The model was run for existing unobstructed conditions and seven different configurations of a simple geometric grid of channel obstructions extending from bankfull stage to the river bed (Figure 5). All model runs assumed steady uniform flow for three representative discharge events: low flow, existing bankfull flow, and flow of record. The model was calibrated for existing conditions (Figure 6a) and using actual field measurements of head loss over channel spanning logjams in different sized channels (PWA 2001). When only one or two logjams were introduced to the model, distinct steps in the water surface profile were predicted (Figure 6b). When five of historic logjams (Figure 4) were input to the model the water surface profile rose significantly and smoothed out (Figure 6c). Hydraulic modeling clearly suggests that channel clearing resulted in lower water elevations within the Ozette River. Logjams imposed significant hydraulic controls that had their most pronounced effect at lower discharges (PWA 2001). Periods of low flow can be critical for salmonids. By increasing water depths in the river two to three times above those in the unobstructed channel with the same discharge, the wetted perimeter of the channel and the habitat available to fish would have been much greater with the logjams intact. Modeling results also suggest that water elevations in Lake Ozette were about one meter more with the logjams than without. Even if lake elevations were slightly higher over longer periods of time, the effect could have been significant for low gradient spawning beaches around the lake. A one-meter rise in lake level would increase the inundation frequency and wave energy necessary to maintain a clean gravel substrate over huge area of shoreline. The Ozette River study was supported by field measurements of an actual logjam in the Deschutes River about 21 km south of Olympia, WA (Figure 1).

Early in the 1990s a large logjam complex began to form within an alluvial reach of the Deschutes river located in a largely undeveloped floodplain of agricultural and forest land. The river has a gradient of 0.003 and bankfull width of abut 35 m. The logjam itself was set within a forested portion of its floodplain, flanked to the west by red alder where the river had migrated in the last 50 years and to the east by a mature stand of large conifers and bigleaf maple. In the winter of 2000-2001, the logjam grew dramatically, ultimately filling more than 400 m of the main-stem channel by February of 2001. River stage upstream of the logjam rose and led to concerns about flood hazards within the reach. Thurston County placed water level recording gages downstream and upstream of the logjam to quantify the magnitude to which the logjam was influencing flood hazards. Gage records indicate that the logjam was raising water elevations approximately 1.4 m (4.5 ft) during low flow periods (Figure 7). This head differential due to the logjam diminishes with increasing discharge, probably since flows are already spreading out across the floodplain (Figure 7 and 8). Thus, as suggested by the Ozette investigation, the logjam's impact is most significant during low flows and much less significant during large magnitude floods (PWA 2001). An increased frequency of floodplain inundation upstream of the logjam did pose a hazard to one home constructed on the floodplain directly adjacent to the river (Figure 8). The logjam formed in a reach with a mature riparian forest. While the effects of the logjams such as the Deschutes can elevate hazards to human development already set within floodplains and CMZs, the effects benefits fluvial ecosystems. The quantity and diversity of aquatic habitat can increase dramatically as larger areas are inundated more frequently and new side channels form around the logjam (Figure 8). The side channels typically have higher pool frequency, greater hydraulic complexity and cover, and much more shade than found in a large main-stem channel. Boundary roughness of side channels and the floodplain also tend to be substantially higher than the main-stem channel. Sedimentation within and upstream of logjams further reduces conveyance of the main-stem channel and drives over-bank flow and channel change (Abbe and Montgomery 2003). Logjams can rapidly elevate a channel bed several meters and create a unique mosaic of intersecting alluvial surfaces within a CMZ (Abbe 2000; Abbe and Montgomery 2003).

The Deschutes River logjam provides an example of a natural process once widespread in rivers throughout the Pacific Northwest. Similar situations are likely to become increasing common with riparian reforestation and when rivers are left undisturbed. The long-term success of river restoration efforts will depend in part on how well we accommodate channel dynamics and potential increases in flood frequency. The Deschutes site presented an outstanding opportunity to rehabilitate fluvial habitat by purchasing property or conservation easements of land within a delineated flood hazard zone and simply allowing natural processes to proceed. While this strategy was considered, traditional practice prevailed and the Deschutes logjam was removed during the summer of 2002.

Wood, Channel Complexity, and Fish Habitat: Big Quilcene and Elwha Rivers

Stable wood in stream channels can have significant hydraulic effects by increasing boundary roughness and forming flow obstructions. The presence of flow obstructions is probably the single most effective means of increasing hydraulic and morphologic diversity within a channel. Flow around a snag or logjam usually "separates" as it moves past the obstruction, forming three distinct flow regions (Abbe 2000): (i) a re-circulation zone (eddy) downstream of the obstruction; (ii) a zone of constricted flow moving past the obstruction; and (iii) a "vortex street" separating the eddy and zone of constricted flow. All these flow patterns result in a complex assemblage of dramatically different velocities and depths within a very small area, each usually associated with different substrate textures. Flow obstructions such as snags and logjams also provide intricate cover and shade. These physical responses translate into diverse habitat types readily utilized by different salmonid species and life stages.

The lower Big Quilcene River provides an example of a dynamic alluvial river which has undergone significant historical change. The Department of Natural Resources of the Skokomish Indian Tribe has begun investigations to work with private landowners and public agencies to rehabilitate a portion of the river's CMZ downstream of State Route 101 in a manner that is compatible with existing development. Historical channel locations since 1936 illustrate frequent channel migration and a gradual simplification of the river's plan-form (Figure 9). The river gradient is about one percent throughout the reach and unvegetated channel widths vary from 12 to 100 m. Channelization of the upper half of the reach has led to incision and disconnected the river from much of its floodplain forest along the north side of the river, clearly evident in 1957 (Figure 9). Most of the floodplain forest north of the river channel has been converted to pasture. Channel complexity within the same reach in 2002 shows a much simpler channel in the upper half of the reach than the downstream half (Figure 10). The most significant differences between the two portions of the reach are the number of logjams and pools. The upstream section has only three pools—one at a natural bedrock outcrop along the right bank and two small pools adjacent to large rock dumped along the left bank to prevent channel migration. The river channel through the project site was repeatedly bulldozed in the mid-1990s and possibly many times prior to that. There are only two deposits of wood debris, both of which are located in ephemeral secondary channels. In contrast, the downstream section has nine pools, all of which occur at snags or logjams. All but two of the 11 deposits of wood debris occur in the active channel. The logjams clearly are the principal mechanism of pool formation in this portion of the Quilcene River and the presence of logjams is coincident with adjacent riparian forest conditions. The high number of logjams in the lower half of the reach occurs adjacent and downstream of where the river is eroding a hillslope with older trees (landslide area in Figure 10). Stable snags and logjams in alluvial rivers tend to form close to a source of larger trees (Abbe and Montgomery 2003; Abbe et al. 2003).

The hydraulic effects of instream wood include changes in water depth, localized water velocity, and substrate characteristics (Lisle 1995; Abbe and Montgomery 1996; Buffington and Montgomery 1999a). Water depth, water velocity, and substrate size have commonly been used to predict available spawning habitat (Milhous 1979; Stalneker 1979). For example, the Instream Flow Incremental Methodology was used in a Big Quilcene River study to predict the instream flow that provides maximum spawning habitat for chinook, coho, and chum salmon, and steelhead trout (Caldwell 1999). However, field observations of redd distribution and density in Olympic Peninsula and Puget Sound lowland streams and rivers suggest that large areas of spawning habitat predicted with existing models is not utilized by salmon (José Carrasquero, unpublished data). For example, in the Swan River basin in Montana over 75% of Bull Trout spawning occurs in less than 10% of the available stream length (Leathe and Enk 1985). Therefore, spawning habitat predicted by traditional parameters may not adequately represent the habitat likely to be utilized. Actual redd location can be used as a biological predictor of available functional spawning habitat.

In the summer of 2002 an experimental logjam was constructed across a plane bed portion of the Quilcene constrained by a gravel dike on the left or north bank as a pilot project for developing larger scale rehabilitation plans (Figure 10). This portion of the river channel was essentially featureless with no variation in bed topography or texture. The objective of the pilot project was to determine whether the logjam would introduce greater physical complexity to the channel and to track the movement of 14 unanchored logs used in the structure. Water surface elevation upstream of the logjam immediately rose about 15 cm after construction was completed in August 2002. The local head differentials introduced by logjams (Figure 11) enhance down- and up-welling into the substrate and connectivity with hyporheic flow. Selection of areas of hyporheic flows for spawning increases the salmonid egg-to-fry survival rate. Upwelling areas tend to improve survival of eggs and emergent fry by modulating the egg incubation environment and increasing the water exchange around the egg pocket, thereby replenishing oxygen and removing metabolites (Bjornn and Reiser 1991; Freeze and Cherry 1979). Hyporheic flow help to modulate the temperature inside redds by proving input of water warmer than the river thus protecting the eggs during periods of extreme low temperature and ensuring emergency at optimal times (Berman and Quinn 1991). Geist and Dauble (1998) found that salmon spawning site selection was closely associated with local hydraulic conditions, particularly areas of up and downwelling flows. Stream habitats selected by bull trout for spawning are influenced by geomorphology and groundwater (Graham et al. 1981; Weaver and White 1985; Baxter and Hauer 2000). Salmon redds in the lower Elwha River increase in density inversely with distance from natural and constructed complex wood accumulations (Figure 12). Several weeks after the Quilcene logjam was constructed, there were 7 redds within 10 m of the structure and none from 10 to 50 m further upstream or downstream. Complex channel patterns promoted by the constructed logjams in the Big Quilcene and Elwha Rivers promote localized variations in bed topography, substrate material and hyporheic flow which in turn influence where salmon spawn in these river reaches.

The Rehabilitation of the Lower Elwha River Valley

Over the last 90 years, upstream dams cut off the sediment supply to the lower Elwha River. Currently much of the lower mainstem Elwha is a relatively wide, shallow coarse cobble bedded channel with little complexity. The western portion of the lower Elwha valley bottom is covered by deciduous forest (Figure 13a). About one third to one half of the lower Elwha CMZ has undergone for agricultural and residential use east of the federal levee (Figure 13a). The best habitat is currently found in the Hunt Road side channel which is heavily loaded with wood debris and flows through older vegetation (40 to 60 years old) along the west side of the floodplain (McHenry et al. 2002). When the Elwha and Glines Canyon dams are removed a large quantity of the sediment stored in the reservoirs will be subject to erosion and introduced into the river (USDI 1996; Pohl 1999). One predicted consequence of this large increase in sediment supply is a meter or more of aggradation in the lower 4 km of the Elwha (USDI 1996). Historical channel rates of the lower Elwha since the dams were constructed have been approximately 5 m/yr. This migration rate is predicted to rise substantially with post-dam removal sedimentation (USDI 1996).

Sedimentation and rapid migration of the channel back and forth across its CMZ will contribute to a loss of floodplain forests through both burial and erosion, respectively. The lower Elwha valley no longer has the big trees that once formed the nuclei for hard points that once created pools and morphological complexity in rivers and floodplains structure in alluvial valleys throughout the Pacific Northwest (Sedell and Frogatt 1984; Abbe and Montgomery 1996, 2003; Collins and Montgomery 2002; O'Conner 2003). Therefore, if stable hard points are not introduced, the channel migration zone could develop into something resembling a braided outwash plain of a river, which has a sediment supply far in excess of the river's transport capacity (Figure 13b). Such a situation could have devastating impacts on the fluvial ecosystem, particularly salmonid habitat and fish passage into the upper Elwha. Spawning gravels would be subjected to frequent burial by fine sediments, pools would be filled, riparian cover dramatically reduced, and floodplain forest development would be limited by repeated erosion associated with channel migration. Given that surface flow in shallow, wide sections of the current main stem channel gets extremely low during dry summers, sedimentation and an even wider braided channel could convert sections of the river into an ephemeral channel, further underlying the need for maintaining pool strings through the CMZ.

Pursuing an alternative strategy of constructing hard points throughout the lower Elwha CMZ offers a realistic means of rehabilitating salmon habitat whether the Elwha dams are removed or not. Sixteen logjams have already been constructed in the Lower Elwha river near the upstream end of the Hunt Road side channel and four more structures will be constructed in 2003 (McHenry 2002). Under existing conditions, logjams provide effective mechanisms for trapping sediment and increasing channel complexity (Abbe and Montgomery 1996, 2003; McHenry 2002). In rivers with extremely low sediment supply naturally, such as the lower Quinault River downstream of Lake Quinault, O'Connor et al. (2003), show that logjams can be the principal agent of channel change. In the case the dams are removed, wood could also be a critical element in recovery of the ecosystem. In systems with elevated sediment supply, wood debris has been shown to be effective at sustaining pools and textural complexity (e.g., Lisle 1995; Lisle and Napolitano 1998; Buffington and Montgomery 1999b). Constructing logjams in the lower Elwha CMZ could be crucial in sustaining a matrix of pools, complex cover, and forest refugia sites (Figure 13c). Fish response to logjams constructed thus far has been very positive (McHenry 2002; Pess et al. 2002). Without such structures to protect patches of ground within the CMZ, frequent oscillation of the channel across its CMZ following dam removal could delay the development of a mature riparian forest. Recovery of the lower Elwha can only really begin when the hard points begin to form again. Given current conditions found in alluvial reaches of the lower Elwha River, post-dam removal recovery could be substantially reduced if proactive efforts such as the construction of logjams near the Hunt Road side channel inlet are not expanded to create a matrix of hard points throughout the river's CMZ.

Conclusions

Alluvial river valleys throughout the Pacific Northwest were once characterized by tremendous physical and biological complexity. Land development during the last 150 years has dramatically reduced the amount of land once part of these fluvial environments and the complexity of fluvial corridors. Public, private and tribal cooperation can lead to successful efforts to reintroduce, sustain, and adapt to the physical changes induced by wood debris and riparian reforestation. The rehabilitation of fluvial ecosystems necessary for salmon recovery will ultimately depend on how far humanity can move from a legacy of simplifying rivers to valuing the inherent complexity and dynamics of these complex environments. Habitat rehabilitation will best be accomplished through collaborative efforts between all stakeholders to better understand fluvial systems and develop sustainable strategies which benefit people and wildlife.

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Figures

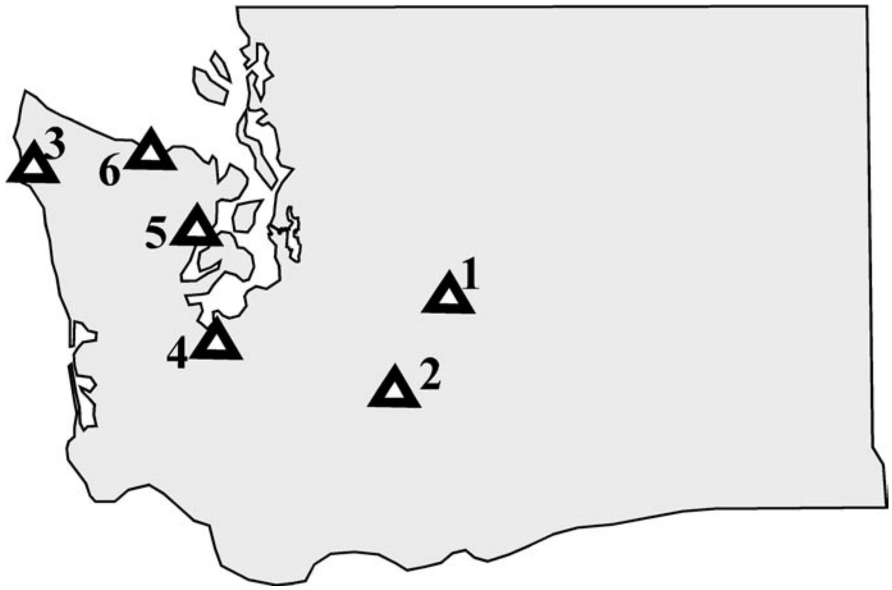

Figure 1. Sites are numbered on the map in the sequence they are presented in the paper. A reach of the Yakima River valley on the east slope of the Cascades provides an example of a river corridor that retains much of its natural complexity despite nearby development (1). Photographs from the Ohanapecosh River illustrate the linkage between forest structure and logjams (2). A brief description of the backwater effects of logjams is presented using examples from the Ozette and Deschutes rivers (3 and 4, respectively). Finally, some of the ecosystem consequences of whether or not stable logjams are restored to river valleys are briefly discussed with examples from the lower Big Quilcene and Elwha river valleys (5 and 6, respectively).

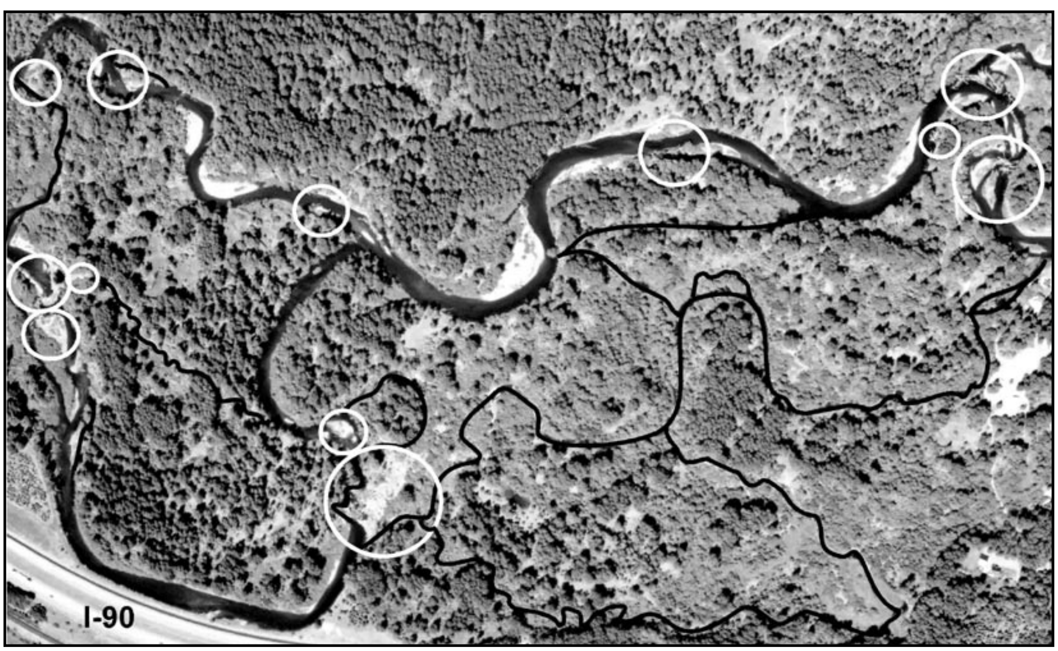

Figure 2. Low gradient alluvial reach of the Yakima River east of Easton, WA, north of Interstate Highway 90 (lower left corner of photo) on August 2, 1998. Flow is left to right. This reach of the Yakima is characterized by multiple channels, a diverse forest assemblage and numerous floodplain wetlands. Several secondary channels are highlighted with black lines. Snags and logjams (white circles) are also abundant in this reach where they obstruct flow, sometimes impounding an entire channel such as the large logjam near the center of the photo.

Figure 3. (a) Example of complex mosaic of channels, logjams and forest structure in the Ohanapecosh River valley (people on the right side of photo provide a scale perspective). This valley bottom primarily consists of relatively young deciduous forest that reflects the frequent channel change characteristic of this reach. Logjams such as in the foreground not only provide substantial benefits to aquatic habitat but can also create hard points that deflect flow and resist erosion by a frequently migrating channel. Logjam hard points form long-term forest refugia which allow small patches of old trees (square in center of photograph) to develop within the channel migration zone (CMZ). **(b)** Example of cedar tree about 4 meters in diameter and more than 500 years old growing on a buried logjam within Ohanapecosh CMZ. Note flotsam (small wood debris) and recent sand deposition in foreground of photo. Behind the cedar is large perennial channel. These large trees ultimately create snags more than sufficient to create a stable logjam, once again re-directing the river.

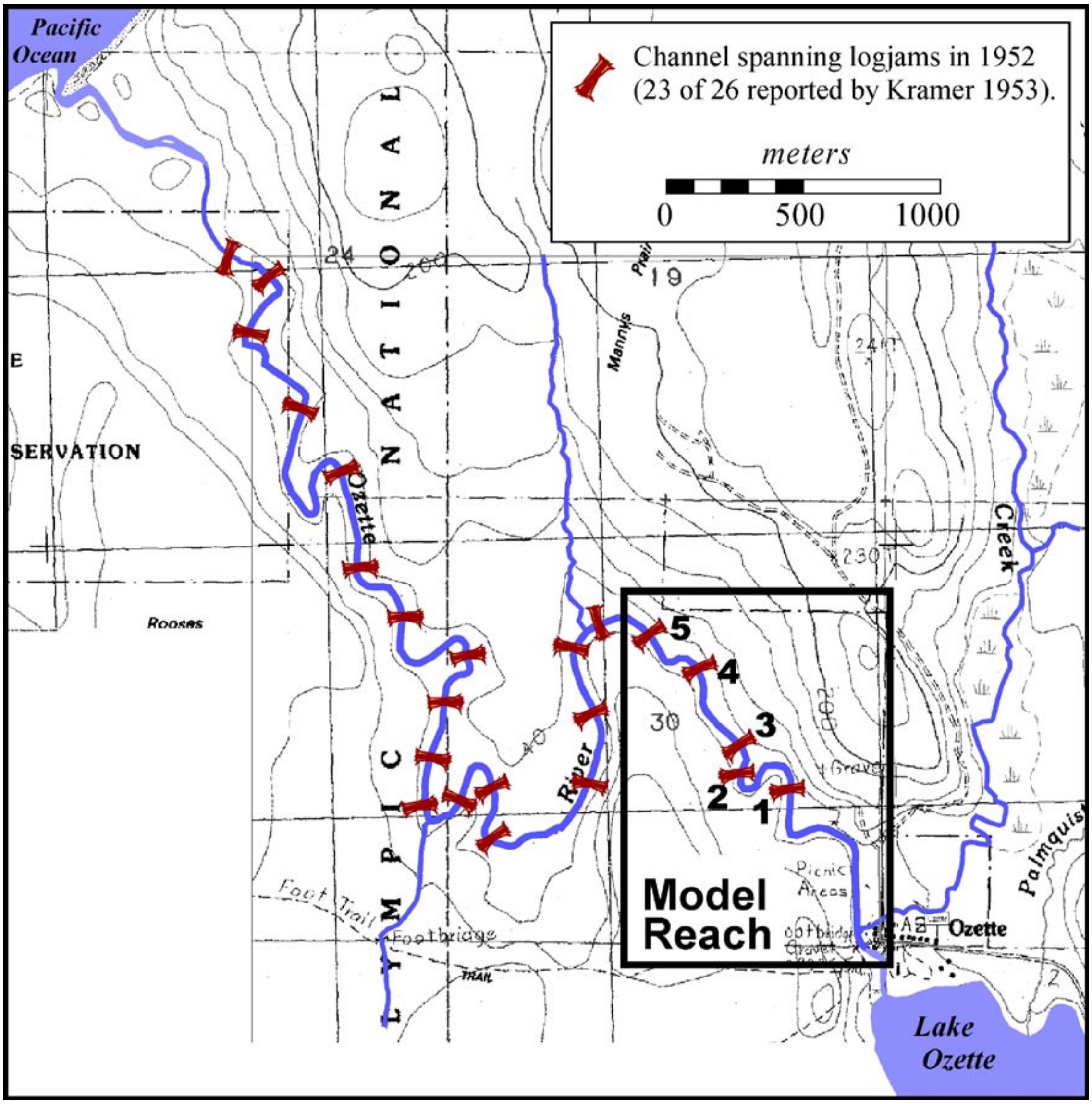

Figure 4. Historic logjam locations in Ozette River. The Ozette River flows about 9 km from Lake Ozette to the Pacific Ocean at the northwest end of the Olympic peninsula. Large logjams, many of which included snags more than 2.5 m in diameter were documented throughout in the Ozette River (Kramer 1953). Logjams certainly had occurred in the river for thousands of years. Channel clearing beginning early in the 20th century culminated in 1952 when dozens of channel spanning logjams were removed from the Ozette River and tributaries to Lake Ozette to improve fish passage (Kramer 1953). The box at the southeast end of the river near the outlet of Lake Ozeette highlights the upper reach of Ozette River surveyed and modeled in 2002. Logjam numbers within the study reach correspond to logjam locations in Figure 6.

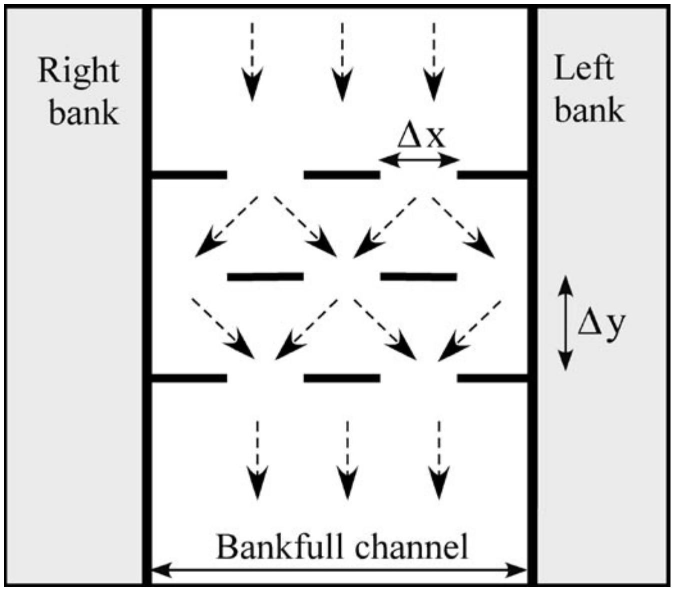

Figure 5. Planview illustration of simple geometric grid of flow obstructions used in hydraulic model to simulate channel spanning logjams. Each plate obstructing flow extends from channel bed to bankfull elevation. The model was run for range of conditions in which the number of rows, row spacing and plate widths were varied (PWA 2002). Model results presented in Figure 6 are based on a five rows with Δx and Δy equal to 1/5 the channel width.

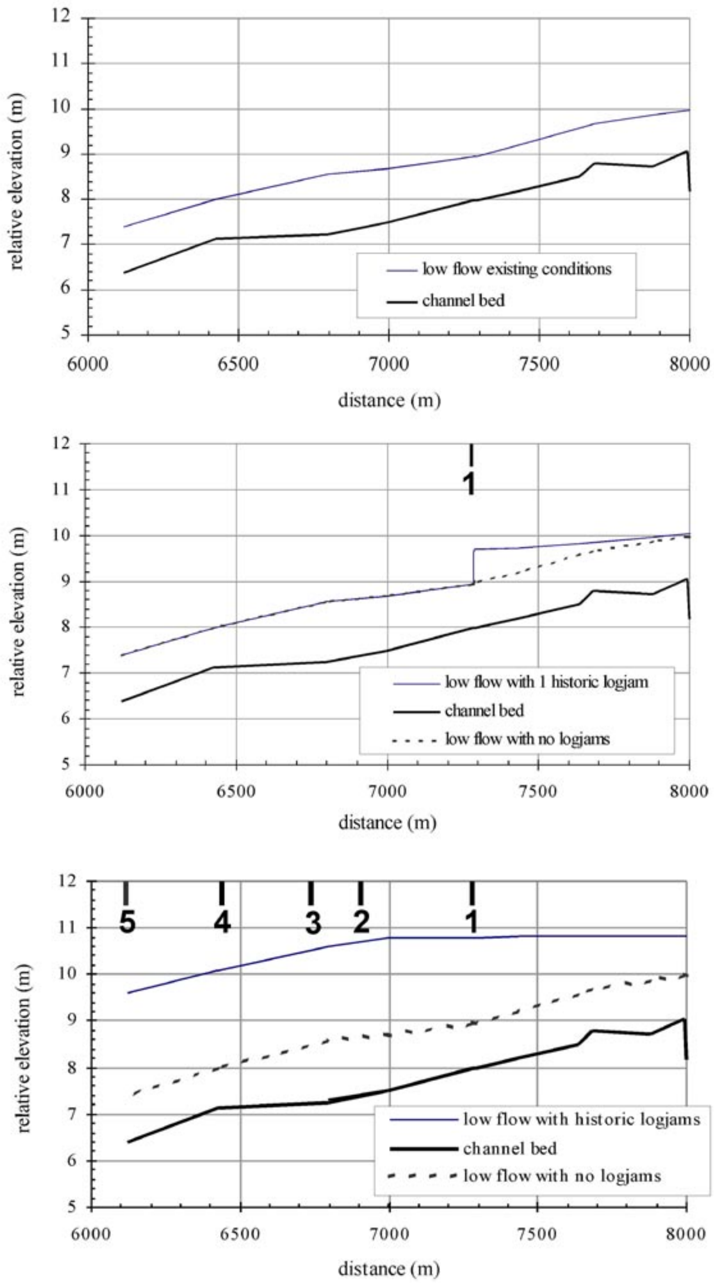

Figure 6. Example of HEC RAS model results for upper 6000 m of the Ozette River reported by (PWA 2002). The same discharge is used in each of the three profiles. **(a)** Modeled water surface profile based on surveyed cross-sections, water surface profile and discharge in September 2002. Lake Ozette is at right.**(b)** Model prediction of re-introducing one logjam at upstream limit of jams mapped by Kramer (1953), noted by tick at top of graph. The logjam forms a step raising the water surface profile directly upstream of the jam, but has not apparent influence on lake elevations at that location. c) Results of introducing four additional logjams at historic locations, with the same model variables used for the single logjam in **(b).** The resulting water surface profile shows a dramatic rise in water surface elevations with a relatively smooth profile. Water depth in the river increases from about 1 m to 3 m, increasing the wetted perimeter of the channel and quantity of aquatic habitat. The model predicts that historic logjams may have maintained a summer lake elevation about 1 m above the current lake level. Such an effect would have had a significant effect on Lake Ozette shorelines, particularly spawning beaches used by sockeye salmon. Hydraulic head gain would also benefit mainstem spawners; because in alluvial reaches it would increase hyporheic flows, which are now known to be critical in the salmonid redd site selection and, likely, in the egg-to fry survival.

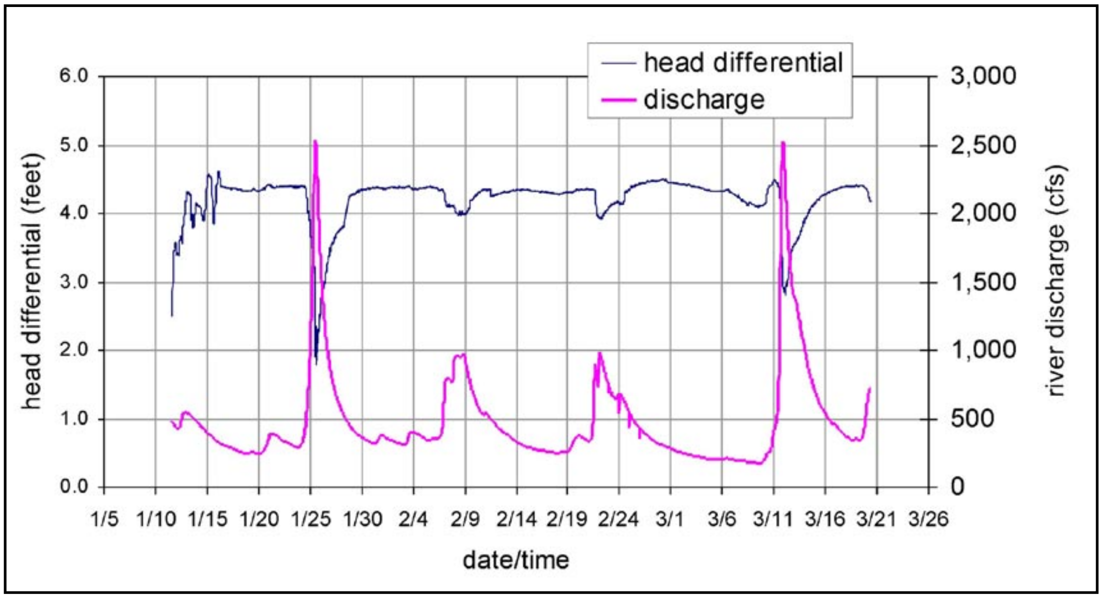

Figure 7. Hydrograph (lower line) and corresponding head differential due to natural logjam (upper line) in Deschutes River south of Olympia, Washington, winter of 2002. Logjam raises low-flow water elevations by approximately 1.4 m (4.5 ft), but the relative contribution on water elevations due to the logjam diminish with increasing discharge. The logjam increases the frequency of floodplain inundation but has relatively little effect on large magnitude floods. The river channel was obstructed by the logjam over a length of about 340 m (1115), diverting flow into secondary channels and across floodplain on either side of the jam (Figure 8). Gage data collected by Thurston County.

Figure 8. **(a)** Aerial photograph of Deschutes river logjam in February 2002. Flow is from bottom to top of photo. Overbank flow is visible near house surrounded by sandbags and in forest on either side of logjam. **(b)** Flow inundating floodplain and carving new side channel on west side of river (location 1 in photo a). Discharge is well below bankfull. **(c)** Conditions same day on the other side of the river (location 2 in photo a) where flow winds through a mature floodplain forest. Approximately 50 m downstream of c) a 1.6 m headcut was progressing upstream through the floodplain and forming a new channel conveying flow around the mainstem logjam.

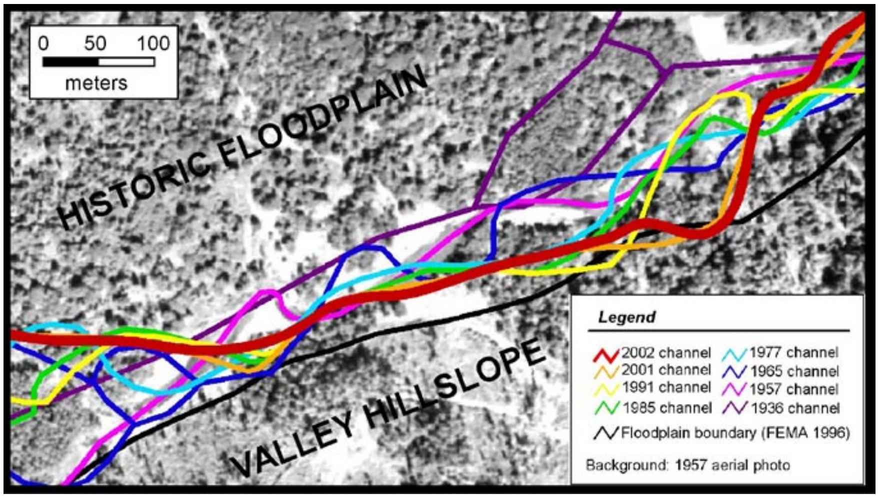

Figure 9. Part of the Big Quilcene River study reach on east side of Olympic Peninsula, flow is from left to right. Aerial photograph presents conditions in 1957. Channel locations since 1936 are mapped in different colors with 2002 channel in bold red line. With the exception of the 1936, channel sinuosity gradually diminishes through time, particularly in the upstream half (west) of the reach. The black line delineates southern margin of floodplain. All of the land north of the channels lies within the floodplain, most of which has been converted to pasture.

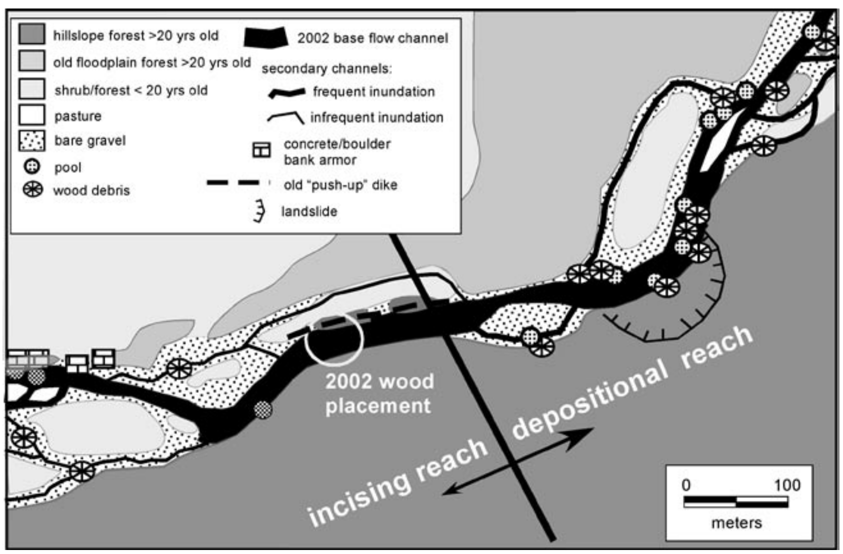

Figure 10. Map depicting snags and pools in 2002 for the same reach of the Big Quilcene River presented in Figure 9. During last 30 years the river was repeatedly cleared and constrained by levees and bank armoring, particularly in the upper half of the reach. In response to these alterations the channel has lost sinuosity and undergone incision which in-turn has disconnected the river from its floodplain and historic channel locations. More of the river's channel migration zone and riparian forest was left intact in the downstream portion of the reach and the channel is considerably more complicated. The lower half of the reach has nine pools, all of which are associated with snags or logjams. In contrast, the incised upper half of the reach has only three pools, one at a bedrock outcrop along the right bank and two beside rock rip-rap placed along the left bank.

Figure 11. Photograph of constructed logjam in Elwha River at upstream end of Hunts Road Side Channel, summer of 2002. Photograph also illustrates upstream velocity head and deep crescent pool adjacent to logjam. Local variations in hydraulic gradients imposed by logjams contribute to hyporheic flow through alluvium. During spawning site selection and construction of redds, salmonids often seek out areas of enhanced flow moving into and out of the channel substrate.

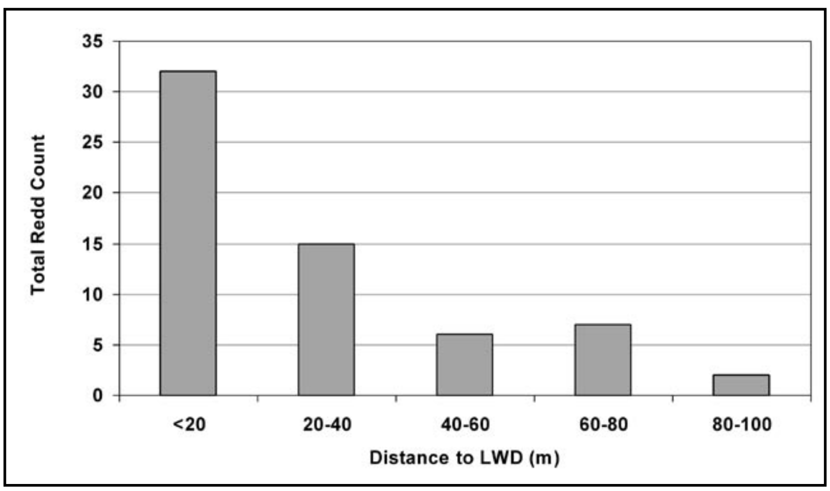

Figure 12. Salmon redd density increases dramatically with increased proximity to logjams constructed in the Lower Elwha River (2001 surveys). Constructed logjams in the Elwha and Quilcene Rivers have been successful at creating and sustaining pools and increasing morphologic and textural complexity of the channel. Logjam performance and persistence are reflected in other engineered logjams projects in the North Fork Stillaguamish and Cispus Rivers where logjams remain intact after being over-topped by as many as 30 peak flows and sustained pools since construction in 1998 and 1999 (Abbe et al. 2003, Abbe et al. in press).

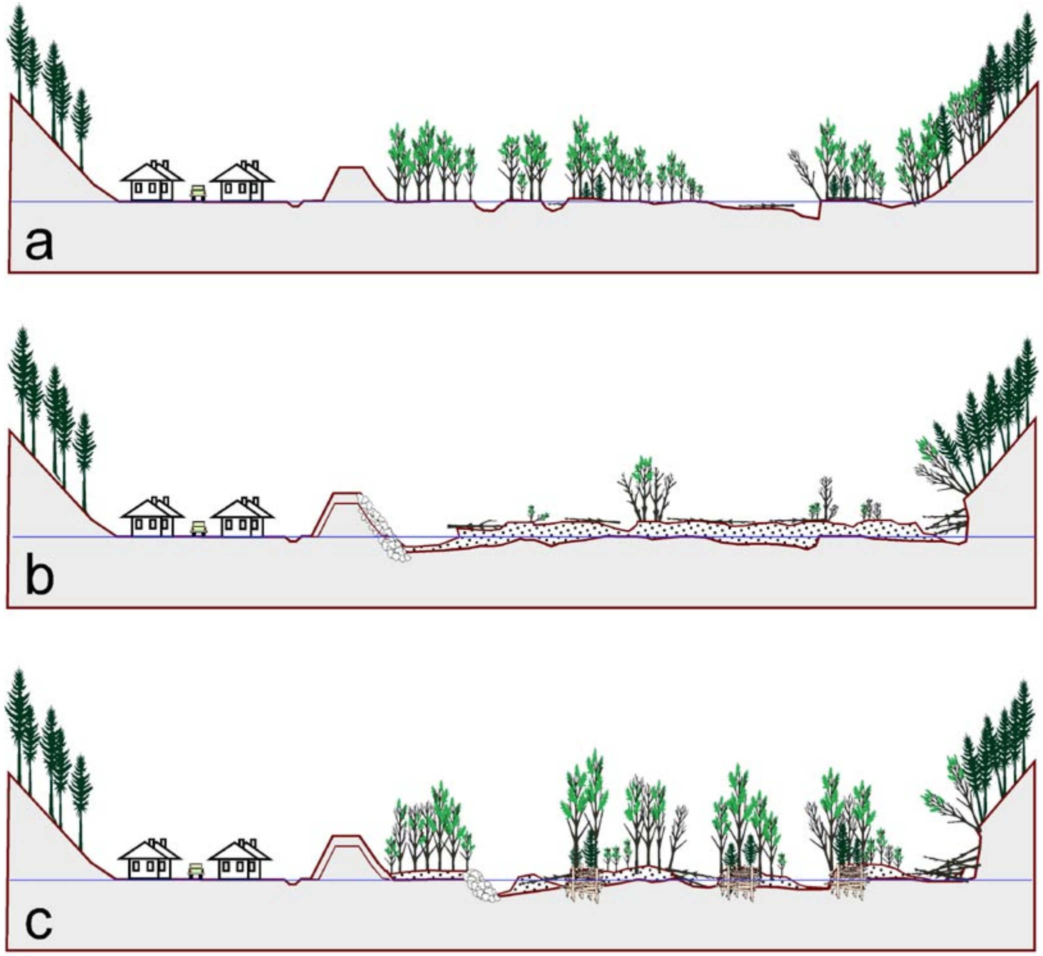

Figure 13. Hypothetical illustrations of two different responses an alluvial river valley could undergo when subjected to an extreme increase in sediment supply such as resulting from dam removal. Initial conditions assume immature forest cover and no hard-points within a CMZ partially constrained by a levee **(a).** The increase in sediment supply is assumed that sedimentation will accelerate channel migration within the CMZ (USDI 1996), which will result in rapid erosion of existing riparian forests and threaten the levee. The first scenario assumes that no hard points are introduced to the CMZ prior to the increase in sediment supply and that a blanket rock revetment is constructed on the levee **(b)**. In this scenario there will be no riparian forest along the river when it flows along the levee since trees are not permitted on federal levees. Sedimentation and the rapidly migrating channel will erode much of the existing forest and inhibit re-forestation **(b)**. The second scenario assumes the system is subjected to the exact same set changes but that hard points are introduced to the CMZ and that the rock revetment protecting the levee is placed some distance from the levee to preserve a riparian buffer between the river and levee **(c)**. In this scenario the hard points protect patches of forest from the migrating channel and impose local hydraulic controls that sustain pools despite sedimentation.